REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE Atomic-scale engineering of magnetic dynamics in ferromagnetic thin films	5. FUNDING NUMBERS DAAD19-02-1-0375
6. AUTHOR(S) William Bailey	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Columbia University 630 West 168th Street, Box 49	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER 43986.3-MS-YIP

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

See Attached Report

14. SUBJECT TERMS	15. NUMBER OF PAGES 6
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Enclosure 1

Project report
MBE deposition of epitaxial $Fe_{1-x}V_x$ films for low-loss Ghz devices; Atomic scale engineering of magnetic dynamics

Grants DA-ARO-W911NFO410168, DA-ARO-DAAD19-02-1-0375 (ARO-43986-MS-YIP)

William Bailey. Columbia University, New York NY

August 18, 2006

Abstract

We report on the deposition of epitaxial iron and iron alloy thin films with the lowest GHz linewidths ever attained in metallic ferromagnets. Maximum half-power Q is shown of 100 at 10 Ghz and 140 at 40 Ghz, significantly higher than known previously for metals.

Background

The goal of this project has been to create metallic ferromagnetic thin films with low microwave (0-40 Ghz) loss. Compared with oxides, metallic ferromagnetic thin films feature high magnetic moments, leading to high operating frequencies, and integrability, with high quality growth attainable at low temperatures (to 200 C). A long range goal is the use of metallic ferromagnets as microwave passive components (frequency-agile inductors, filters, circulators) in MMIC platforms, saving space and weight compared with bulk ferrite components, which are diced and glued in place. An "achilles heel" for metallic ferromagnets is their high loss compared with oxides, such as YIG.

Previous work of PI

The fundamental limit for loss is the intrinsic relaxation rate G. In the limit of low extrinsic loss at relatively low frequency, there is a simple relationship between G and ferromagnetic resonance (microwave absorption) frequency linewidth Δf and G: $\Delta f = 2G$. G is an essential parameter for microwave applications. Lowest values have been found in the past for pure iron (Fe), with G to 57 Mhz[1, 2], although a range of G from 57 to 140 Mhz is cited typically in Fe[3].

In previous studies under 43986-MS-YIP, we had identified $Fe_{1-x}V_x$ as a material which showed lower values of intrinsic Gilbert relaxation rate G than seen in Fe. G was reduced substantially upon addition of V in epitaxial Fe(50nm) thin films on MgO(100). Overall linewidths were high, however, with G of 140 Mhz found for the pure Fe, with a large inhomogeneous component present as well. (See 43986-MS-YIP final report.)

Technical goal of project

The goal of the STIR project was to bring inhomogeneous losses under control, improving microwave performance. As stated (boldly) in the proposal abstract,

> *In this short-term innovative request, we intend to create magnetic thin films with the lowest values of loss ever demonstrated.*

A newly constructed MBE chamber, supported through a DURIP award, was to be instrumental.

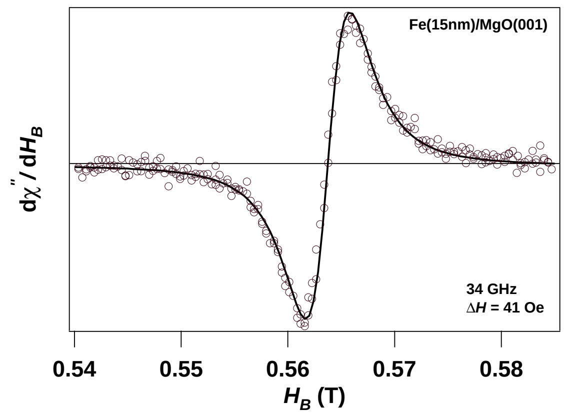

Figure 1: Epitaxial MgO(100)[100]/ Fe(100)[110] (15nm) thin film, with lowest 35 GHz FMR linewidth ever seen in a ferromagnetic metal. Scheck et al[5].

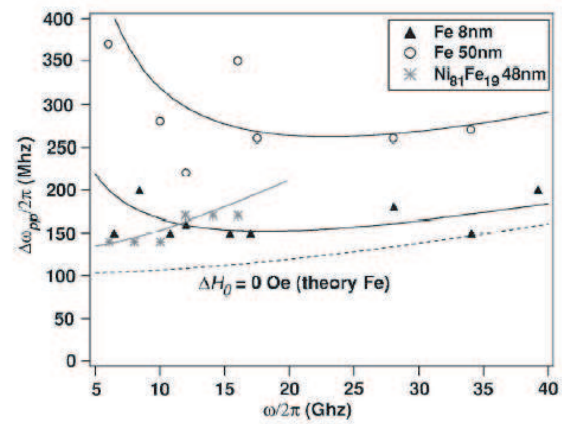

Figure 2: Frequency linewidths Δf_{pp} for epitaxial Fe, compared with $Ni_{81}Fe_{19}$. Convert to half-power $\Delta f_{1/2}$ by $\sqrt{3}$. Lines are theoretical fits. Scheck et al [5]

Project achievements

We have delivered on the technical goals in several respects. We have shown:

- **Lowest total losses in pure Fe films.**

  A simplest measure of loss is swept-field FMR linewidth ΔH_{pp}, the most typical experimental observable. It can be used as a direct comparison with previous results. The lowest recorded 35 Ghz linewidth in a ferromagnetic metal was for MBE deposited epitaxial Fe(15nm) on ZnSe/GaAs[4]: ΔH_{pp} = 45 Oe, using MBE deposited Fe(15 nm). Other Fe films have not been close; typical values for sputtered or MBE-deposited films are on the order of 100 Oe.

  In Fig 1, we show ΔH_{pp} = 41 Oe in films of comparable thickness.

- **$Q > 100$ in pure Fe at 30-40 Ghz**

  The frequency domain performance was even more impressive. Swept-frequency half-power linewidths at 35 Ghz were seen of a minimum of 250 Mhz, yielding Q of 140. Our demonstrated Q is an order of magnitude higher than reported prevously by ARO-supported groups[6, 7].

  Note the superiority of Fe-based films for frequency-domain applications in Figure 2. Δf starts out limited by G, and begins to increase at higher frequencies where $H \sim 4\pi M_s$. These two facts highlight shortcomings of well-known ferromagnetic alloys such as $Ni_{81}Fe_{19}$: though inhomogeneous losses can be made low, G is high (125 Mhz) and M_s is low, pushing the increase to lower frequencies. Thin Fe clearly outshines $Ni_{81}Fe_{19}$ at 30-40 Ghz.

- **Lowest intrinsic loss in epitaxial $Fe_{1-x}V_x$**

  Intrinsic and extrinsic (defect-related) losses are typically separated through variable-frequency FMR; the offset in $\Delta H(\omega)$ gives the extrinsic loss, and the slope the intrinsic loss. A wide frequency range is helpful for separation; our spectrometer is limited to 40 Ghz. We have measured to 70 Ghz in collaboration with Zdenek Frait at the Czech Academy of Sciences. We find (as expected from previous work) that α (slope) is largely unchanged on adding V, but $G = \alpha\gamma M_s$ is reduced, as the moment is reduced.

  The obtained value of $G = 35 \pm 5$ Mhz is the lowest ever found in a ferromagnetic metal. *This*

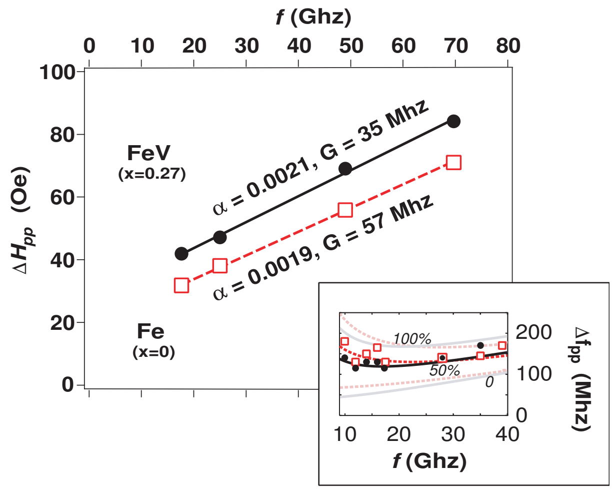

Figure 3: Separation of intrinsic G and extrinsic loss ΔH_0 for Fe and $Fe_{1-x}V_x$ using 18-70 Ghz FMR, showing 40% lower G for the V alloy. *Inset*: swept-frequency linewidths.

result is analogous to finding a metal with a lower room temperature resistivity than copper! Fe has been known as the lowest loss ferromagnet for many years.

- $Q \sim 100$ **in** $\mathbf{Fe_{1-x}V_x}$ **at 10-20 Ghz**

  The $Fe_{1-x}V_x$ film exhibits lower frequency linewidths than the Fe film, by some 10-30 Mhz over this frequency range. Minimum values are near 100 Mhz, significantly lower than the theoretical limit for $Ni_{81}Fe_{19}$ in the low frequency limit (150 Mhz), in the absence of inhomogeneous loss. Note also that these values can be reduced further if inhomogeneous loss is eliminated; $Fe_{1-x}V_x$ has a theoretical limit for $\Delta f_{pp} = 40$ Mhz, see zero inhomogeneous loss curve, corresponding to Q up to 200.

Outlook

What is quite remarkable about the results is that they were obtained in UHV sputtered films. Sputtered films, in fact, are thought to have low G due to a smaller density of point defects due to higher adatom energy, but suffer from high ΔH_0 from line defects.[1] Inhomogeneous losses have been reduced all the way to zero in MBE deposited Fe, but with relatively high $G > 140$ Mhz[8]

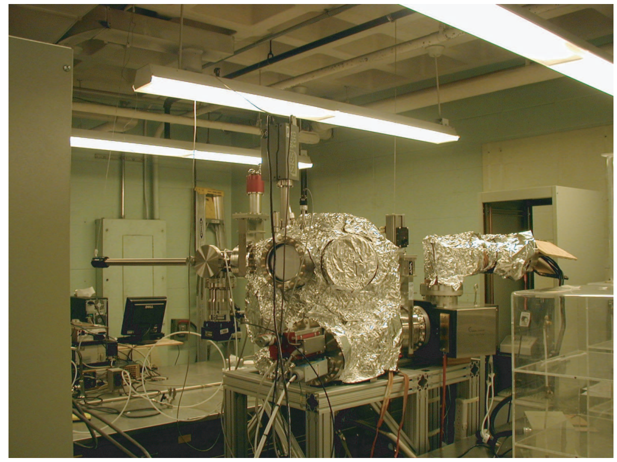

Figure 4: Newly constructed MBE deposition system in Mudd 172, Columba University. System is pictured with load lock, 30 kV RHEED gun and screen, 5-pocket e-beam evaporator, turbopump, ion pump and titanium sublimation pump with cryoshroud (right), and is at a base pressure of 4×10^{-10} Torr at the time of writing

.

We have found that there are three critical issues for high quality epitaxial UHV sputtered films. Temperature must exceed 200 C. The cap layer is extremely important; our best results have been with Ti or Au caps. Finally there is a very narrow window during which sputtered Fe returns good results: the target racetrack needs to be very thin so that deposition rates are high, but not so thin that the target sputters through. This comprises something like 10% of the 1/16" target lifetime, in our experience.

MBE system We have pursued these films while completing construction of the MBE chamber. Presently the MBE system lacks only a sample ma-

[1] Private communication from Bret Heinrich

nipulator; it has functional turbo, ion, sublimator pumps, is leak tight to a base pressure of 5×10^{-10} Torr, and has loadlock, RHEED, and 5-pocket 3kW electron beam evaporation source installed. To start producing films, the chamber requires: 1) machining of the sample manipulator, which has been contracted and due for completion within the month, 2) incorporation of UHV translation stages (linear shift and rotation) for sample manipulation. Also remaining to be completed are 3) installation of the ion beam assist gun, and 4) incorporation of the STM.

The time scale for the project has largely been set by the vendors, who have been significantly late in delivering first the chamber drawings (two months), then the chamber (four months), and then functional pumps (six additional months of returning defective items). Our delivery of detailed CAD to the vendor, as well as receipt of all components to be assembled at Columbia, was complete in August 2005.

Fortunately we have not needed the MBE system to deliver on the project goals. Our ferromagnetic films have the best microwave propoerties seen anywhere. However, it may be possible to achieve even better films in MBE, particularly using the additional control available through ion beam assist; one could imagine defining low misfit defects in the first several layers using conventional MBE, and introducing the ion bombardment to mimic sputtered films for low G.

Outputs

The project funds were used to support Christian Scheck, a postdoc, and Lili Cheng, a Ph.D. candidate in the final stages of completing her disseration. Scheck was dedicated 100% of the time to epitaxial $Fe_{1-x}V_x$ film deposition, FMR characterization, and chamber construction. An additional Ph.D. student, Pratap Ranade, was dedicated 100% of time to chamber design and construction; he was supported by the N.S.F.

Ph. D. theses completed

- "Materials-based control of relaxation in magnetic thin films," Lili Cheng, Materials Science and Engineering, Columbia University, deposited Jan. 2006. (Lili is now a postdoctoral scholar at Los Alamos National Lab, working with Scott Crooker).

Publications

Direct relationship with project activities

- "Low damping in epitaxial sputtered iron films," C. Scheck, L. Cheng, W.E. Bailey, *Applied Physics Letters* **88**(25) 252510 (July 2006)
- "Lowest intrinsic relaxation rate in a ferromagnetic metal," C. Scheck, L. Cheng, I. Barsukov, Z. Frait, W.E. Bailey, *submitted July 30 2006*, under review.

Indirect relationship (precession and relaxation), partial list

- "Weakly coupled precession of individual layers in ferromagnetic resonance," D.A. Arena, E. Vescovo, C.-C. Kao, Y. Guan, and W.E. Bailey, *Physical Review B* **74**(6) 064409 (Aug 2006)
- "Dual-frequency ferromagnetic resonance," Y. Guan and W.E. Bailey, *Review of Scientific Instruments* **77**(6) 053905 (May 2006)

Presentations (selected)

Direct relationship with project activities

- *oral*: "Reduced spin lattice coupling and Gilbert damping in epitaxial $Fe_{1-x}V_x$ thin films," C. Scheck, L. Cheng, W.E. Bailey, *Materials Research Society Spring Meeting*, San Jose CA, Oct 30-Nov 4 2005.
- *invited talk*: "Atomistic basis of precessional dynamics in ferromagnets," Seagate Research Labs, Pittsburgh PA, Mar 2006.
- *oral*, "Reduced spin lattice coupling and Gilbert damping in epitaxial $Fe_{1-x}V_x$ thin films," C. Scheck, L. Cheng, W.E. Bailey, *Magnetism and Magnetic Materials Conference*, San Jose CA, Oct 30-Nov 4 2005.

Indirect relationship (partial list)

- *invited*: "Layer-specific ferromagnetic resonance," D.A. Arena, E. Vescovo, C.-C. Kao, Y. Guan, and W.E. Bailey, American Vacuum Society Meeting, Boston MA 0ct. 2006.
- *invited*: "Layer-specific ferromagnetic resonance," D.A. Arena, E. Vescovo, C.-C. Kao, Y. Guan, and W.E. Bailey, Joint MMM/INTERMAG Conference, Baltimore MD Jan 2007.

Bibliography

[1] Z. Frait and D. Fraitova, "Ferromagnetic resonance and surface anisotropy in iron single crystals," *Journal of Magnetism and Magnetic Materials*, vol. 15-18, no. pt.2, pp. 1081 – 2, 1980.

[2] F. Schreiber, J. Pflaum, Z. Frait, T. Mughe, and J. Pelzl, "Gilbert damping and g-factor in Fe_xCo_{1-x} alloy films," *Solid State Communications*, vol. 93, no. 12, pp. 965–8, 1995.

[3] M. Stearns and editor, *Landolt-Bornstein Tables*, ch. III-13: 1.1.2.10 (Fe, Co, Ni: g-factors and ferromagnetic resonance properties), pp. 86–91. Dusseldorf: Springer-Verlag, 1990.

[4] G. Prinz, B. Jonker, J. Krebs, J. Ferrari, and F. Kovanic, "Growth of single crystal bcc alpha - Fe on ZnSe via molecular beam epitaxy," *Applied Physics Letters*, vol. 48, no. 25, pp. 1756–8, 1986.

[5] C. Scheck, L. Cheng, and W. Bailey, "Low damping in epitaxial sputtered Fe films," *Applied Physics Letters*, vol. 88, no. 18, p. 252510, 2006.

[6] B. Kuanr, Z. Celinski, and R. Camley, "Tunable high-frequency band-stop magnetic filters," *Applied Physics Letters*, vol. 83, no. 19, pp. 3969 – 71, 2003.

[7] W. Wu, C. Lee, C. Tsai, J. Su, W. So, J. Yoo, and R. Chuang, "Fabrication of ferromagnetic/semiconductor waveguide structures and application to microwave bandstop filter," vol. 19, p. 1758, 2001.

[8] B. Heinrich, Y. Tserkovnyak, G. Woltersdorf, A. Brataas, R. Urban, and G. Bauer, "Dynamic exchange coupling in magnetic bilayers," *Physical Review Letters*, vol. 90, no. 18, pp. 187601 – 1, 2003.